ARIZONA DEPARTMENT OF TRANSPORTATION

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EFFECT OF RIGHT TURNING VEHICLES ON TRAFFIC SIGNAL VOLUME WARRANTS

State of the Art

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16. ABSTRACT

Nationally accepted traffic signal warrants are provided in the Manual on Uniform Traffic Control Devices (MUTCD). There are 11 warrants recommended in the MUTCD; four of these are vehicular volume related warrants. These warrants are: Warrant No. 1 - Minimum Vehicular Volume; Warrant No. 2 - Interruption of Continuous Traffic; Warrant No. 9 - Four Hour Volume; and Warrant No. 11 - Peak Hour Volume.

In all four of these warrants the minor street minimum hourly volume is defined. This volume is the total volume of right turn, through, and left turn movements from the minor street approach. A recent change to the MUTCD states that a portion of the right turn volume may be deducted from the total minor street approach volume:

> **"The analysis should consider the effects of the right turn vehicles from the minor street approaches. Engineering judgment should be used to determine what, if any, portion of the right turn traffic is subtracted from the minor street traffic count when evaluating the count against the above warrants."**

This study: 1) developed a state-of-the-art report on the topic of "Effect of Right Turning Vehicles on Traffic Signal Volume Warrants"; 2) recommended that further research be done leading to the development of guidelines for excluding or including right turning vehicles in the total approach volume for evaluation of the need for a traffic signal; and 3) developed a research work plan for the future.

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INTRODUCTION

The installation or removal of traffic signals is a challenging task that most traffic engineers are faced with. Nationally accepted traffic signal warrants are provided in the Manual on Uniform Traffic Control Devices (MUTCD). There are 11 warrants recommended in the MUTCD; four of these are vehicular volume related warrants. These warrants are:

Warrant No. 1: Minimum Vehicular Volume

Warrant No. 2: Interruption of Continuous Traffic

Warrant No. 9: Four Hour Volume

Warrant No. 11: Peak Hour Volume

In all four of these warrants the minor street minimum hourly volume is defined. This volume is the total volume of right turn, through, and left turn movements from the minor street approach. A recent change to the MUTCD states that a portion of the right turn volume may be deducted from the total minor street approach volume:

> "The analysis should consider the effects of the right turn vehicles from the minor street approaches. Engineering judgment should be used to determine what, if any, portion of the right turn traffic is subtracted from the minor street traffic count when evaluating the count against the above warrants."

While sound engineering judgment is essential in any evaluation of signal needs, the recent MUTCD change still leaves great latitude for discretion in the application of numerical standards for volume warrants, and such variation is not conducive to the uniformity needed to ensure effectiveness of a traffic control device.

RESEARCH OBJECTIVES

The objectives of this study are: 1) to develop a state-of-the-art report on the topic of "Effect of Right Turning Vehicles on Traffic Signal Volume Warrants"; 2) to recommend whether research should be done on this subject; and 3) to develop a research work plan for any recommended research. Any recommended research should lead to the determination of the effect of right turning vehicles on the need for traffic signalization and the establishment of guidelines for typical application of the traffic signal volume warrants. This study was comprised of the four following tasks.

1) Review the current practice in consideration of the effects of right turning vehicles in the total approach volume for determination of traffic signal needs.
2) Review the available research studies addressing the subject problem.
3) Make a recommendation on the scope and the extent of further studies leading to the development of guidelines for excluding or including right turning vehicles in the total approach volume for evaluation of the need for a traffic signal.
4) Develop a detailed work plan for any recommended research and establish the anticipated project duration and estimated budget.

CURRENT PRACTICE

A two page survey was developed to review current practice with respect to this new provision in the MUTCD and to compile a list of factors that are being considered by traffic engineers. The survey was distributed to members of the AASHTO Traffic Engineering Subcommitee (the State Traffic Engineers from each of the 50 states) at its June 22, 1987 meeting. In addition, the survey was mailed to selected members of the National Committee on Uniform Traffic Control Devices. Figure 1 displays the survey form.

Sixty-seven responses were received. Forty-two responses were from state traffic engineers, fourteen responses were from cities, and eleven were from counties. Fifty-seven of the 67 respondents answered "Yes" for question 1 which means that their agency does consider the effects of right turning vehicles from the minor street in applying the volume warrants. The other ten respondents said "No" to question 1. A positive response rate of 85 percent was recorded for question 1.

The 57 respondents that indicated "Yes" for question 1 were then asked to mark the factors that they consider in determining how much of the right turn volume should be included in the minor street volume (Question 3). The statistics of this question are provided in Table 1. The factor that received the highest markings was related to presence or absence of an exclusive right turn lane.

The ten respondents that said "No" to question 1 were asked to mark the factors that they thought should be considered in determining how much of the right turn volume should be included in the minor street volume (Question 2). The results are shown in Table 2. Similar to the findings of question 3, the

NATIONAL COMMITTEE ON UNIFORM TRAFFIC CONTROL DEVICES

c/o Department of Civil Engineering • Arizona State University • Tempe, AZ 85287
602/965-1713

A RECENT CHANGE TO THE MUTCD AFFECTS APPLICATION OF THE TRAFFIC SIGNAL VOLUME WARRANTS. THE MANUAL NOW SAYS THAT THE EFFECT OF RIGHT TURN VEHICLES FROM THE MINOR STREET APPROACHES SHOULD BE CONSIDERED WHEN VOLUME WARRANTS ARE BEING APPLIED. PRESUMABLY, RIGHT TURNING VEHICLES FROM THE MINOR STREET MAY NOT REQUIRE AN INTERRUPTION OF TRAFFIC (BY A TRAFFIC SIGNAL) TO EXECUTE THE RIGHT TURN MANEUVER.

THE EXACT TEXT NOW IN THE MUTCD READS AS FOLLOWS.

> "THE ANALYSIS SHOULD CONSIDER THE EFFECTS OF THE RIGHT TURN VEHICLES FROM THE MINOR STREET APPROACHES. ENGINEERING JUDGEMENT SHOULD BE USED TO DETERMINE WHAT, IF ANY, PORTION OF THE RIGHT TURN TRAFFIC IS SUBTRACTED FROM THE MINOR STREET TRAFFIC COUNT WHEN EVALUATING THE COUNT AGAINST THE ABOVE WARRANTS."

THE NATIONAL COMMITTEE IS INTERESTED IN FINDING OUT HOW THIS NEW PROVISION IS BEING APPLIED. THE MANUAL SAYS THAT "ENGINEERING JUDGEMENT" SHOULD BE USED. WE WOULD LIKE TO FIND OUT WHAT FACTORS ARE BEING CONSIDERED BY THE TRAFFIC ENGINEER. YOUR RESPONSE TO THIS SURVEY WILL BE HELPFUL.

1. IN APPLYING THE VOLUME WARRANTS, DOES YOUR AGENCY NOW CONSIDER THE EFFECTS OF RIGHT TURNING VEHICLES FROM THE MINOR STREET?

   ___YES (PROCEED TO QUESTION 3)

   ___NO (PROCEED TO QUESTION 2)

2. WHAT FACTORS DO YOU THINK SHOULD BE CONSIDERED IN DETERMINING HOW MUCH OF THE RIGHT TURN VOLUME (IF ANY) IS INCLUDED IN THE MINOR STREET APPROACH VOLUME?

   ___NUMBER OF LANES ON THE MINOR STREET APPROACH

   ___PRESENCE OR ABSENCE OF EXCLUSIVE RIGHT TURN LANE

   ___PRESENCE OR ABSENCE OF FREE FLOW RIGHT TURN (RIGHT TURN DOES NOT YIELD TO MAJOR STREET TRAFFIC)

   ___AVAILABILITY OF GAPS IN MAJOR STREET TRAFFIC

   ___SIGHT DISTANCE AVAILABLE TO RIGHT TURNING VEHICLES

   ___PERCENTAGE OF MINOR STREET TRAFFIC WHICH TURNS RIGHT

   ___"TEE" INTERSECTION VERSUS "4-LEGGED" INTERSECTION

   ___PEDESTRIAN VOLUMES

   PLEASE LIST OTHER FACTORS THAT YOU THINK SHOULD BE CONSIDERED.

   _____

   _____

   _____

PROCEED TO QUESTION 5

FIGURE 1. QUESTIONNAIRE

3. WHAT FACTORS DO YOU CONSIDER IN DETERMINING HOW MUCH OF THE RIGHT TURN VOLUME (IF ANY) IS INCLUDED IN THE MINOR STREET APPROACH VOLUME?

___THE PROPORTION OF RIGHT TURN VOLUME INCLUDED IN THE MINOR STREET APPROACH VOLUME IS SIMPLY BASED UPON ENGINEERING JUDGEMENT.

___NUMBER OF LANES ON THE MINOR STREET APPROACH

___PRESENCE OR ABSENCE OF EXCLUSIVE RIGHT TURN LANE

___PRESENCE OR ABSENCE OF FREE FLOW RIGHT TURN (RIGHT TURN DOES NOT YIELD TO MAJOR STREET TRAFFIC)

___AVAILABILITY OF GAPS IN MAJOR STREET TRAFFIC

___SIGHT DISTANCE AVAILABLE TO RIGHT TURNING VEHICLES

___PERCENTAGE OF MINOR STREET TRAFFIC WHICH TURNS RIGHT

___"TEE" INTERSECTION VERSUS "4-LEGGED" INTERSECTION

___PEDESTRIAN VOLUMES

___OTHER (PLEASE DESCRIBE WHAT FACTORS YOU CONSIDER)_____

_____

_____

_____

_____

_____

4. DOES YOUR AGENCY HAVE ANY WRITTEN GUIDELINES FOR DECIDING HOW MUCH OF THE RIGHT TURN VOLUME IS INCLUDED IN THE MINOR STREET APPROACH VOLUME?

___YES (MAY WE CONTACT YOU LATER TO GET MORE INFORMATION? _____)

___NO

5. NAME _____

AGENCY _____

THANK YOU FOR YOUR HELP

PLEASE RETURN TO JONATHAN UPCHURCH THIS WEEK IN CHARLESTON OR MAIL TO THE NATIONAL COMMITTEE OFFICE (ADDRESS ON FIRST PAGE) BY JULY 7, 1987.

FIGURE 1. (Continued)

TABLE 1. RESPONSE RESULTS TO QUESTION 3

Factor Description	Number of Responses	Rank (based on Number of Responses)
Proportion of right turn volume is simply based on engineering judgment	24	6
Number of lanes on minor street approach	28	5
Presence or absence of exclusive right turn lane	42	1
Free flow right turn availability	33	2
Gaps in major street	22	7
Sight distance availability	30	3
Percentage of minor street traffic turning right	29	4
"Tee" versus "4-Legged" intersection	9	9
Pedestrian Volumes	13	8
Others*	9	9

*Examples of Others:

Width of marked lanes

Length of right turn lane

The angle of intersection approach

The grade of the approach

The speed on the major street

Delay to vehicles following right turners

Probability of Right-Turn-On-Red being restricted if intersection were to be signalized

Parking/No parking in curb lane of major street

TABLE 2. RESPONSE RESULTS TO QUESTION 2

Factor Description	Number of Responses	Rank
Number of lanes on minor street approach	7	3
Presence or absence of exclusive right turn lane	12	1
Free flow right turn availability	11	2
Gaps in major street	6	5
Sight Distance Availability	6	5
Percentage of minor street traffic turning right	6	5
"Tee" versus "4-legged" intersection	7	3
Pedestrian volumes	6	5
Others*	2	9

*1. Number of minor street right turners

2. Right turn accident analysis

exclusive right turn lane and the free flow right turn availability are the two factors that were ranked first and second, respectively.

Question 4 was developed to collect information on any written guidelines developed by the respondent agency on how much of the right turn volume is included in the minor street approach volume. Four respondents responded, "Yes," and 63 indicated, "No." The responses to questions 1 and 4 reveal that while 85 percent of those surveyed claim to consider the effects of right turning vehicles, only six percent have any written guidelines describing how they consider the effect. This suggests that nearly all agencies are currently using engineering judgement to determinethe portion of right turning vehicles to include in the minor street volume. The following paragraphs report on the written guidelines used in the four jurisdictions which have written guidelines - Montgomery County, Maryland; Arlington, Texas, and the states of Utah and Oregon.

The first written guideline was received from Montgomery County, Maryland. A decision was made by the County's Division of Traffic Engineering to allow exclusion of a portion of the right turn traffic volume when considering satisfaction of warrant #2 (Interruption of Continuous Traffic Warrant). The exclusion percent is determined by engineering judgment based on field observations during peak hours of operation. It is suggested that delays in excess of 60 seconds for right turns from the side street be considered significant, and that the percent excluded be related to the amount of right turn traffic having delays of less than 60 seconds. A table was designed (Table 3) to facilitate the application of this policy for signal warrant investigation.

The city of Arlington, Texas Department of Transportation provided the second written guideline. The Arlington guideline is subjective, like the other guidelines, which were identified. It is reproduced below.

> Under certain circumstances right turn volumes at an intersection should not be included in the traffic volume warrants because a proposed signal will have little impact on them. The traffic engineer needs to determine the extent of right turn traffic which will affect the main street and side street volumes when signalization occurs. If one or more of the following conditions exists for an approach, right turn volumes should be excluded from the warrant analysis:

DIVISION OF TRAFFIC ENGINEERING
MONTGOMERY COUNTY, MARYLAND

3-78

TRAFFIC SIGNAL WARRANT SHEET

INTERSECTION: _____ at _____ DATE OF COUNT: _____

HOUR BEGINNING	MAJOR APPROACH VOLUMES (BOTH DIRECTIONS) V.P.H.	MINOR APPROACH VOLUMES (HIGHER VOLUME - ONE DIRECTION) V.P.H.			MINIMUM VEHICULAR VOL. (WARRANT I)			INTERRUPTION OF CONT. TRAFFIC (WARRANT II)			REMARKS
		TOTAL	T + L + * % R	APPROACHING FROM	100 % : :	80% : :	70 % : :	100 % : :	80 % : :	70 % : :	
7:00 A.M.											
8:00 A.M.											
9:00 A.M.											
10:00 A.M.											
11:00 A.M.											
12:00 NOON											
1:00 P.M.											
2:00 P.M.											
3:00 P.M.											
4:00 P.M.											
5:00 P.M.											
6:00 P.M.											
				TOTAL							

[_____ APPROACH _____ % R
[_____ APPROACH _____ % R

x WARRANT SATISFIED
C WARRANT NEARLY SATISFIED

TABLE 3. MONTGOMERY COUNTY TRAFFIC SIGNAL WARRANT SHEET

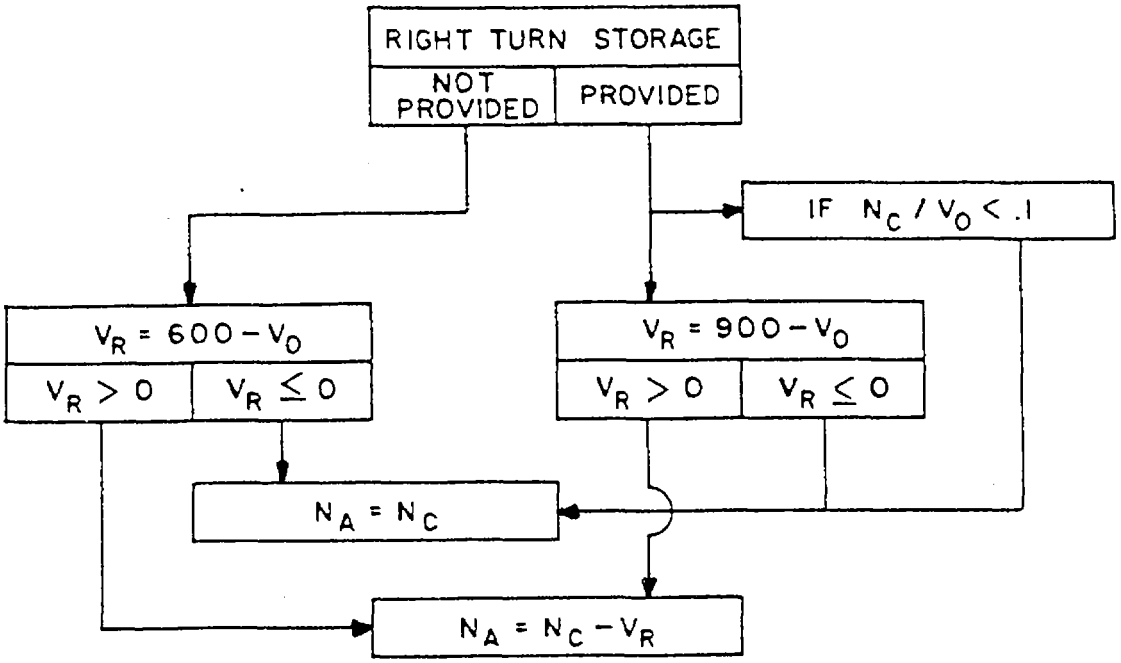
* Where a separate right turn lane or large radius right turn island exists for a side street approach.
* Where a separate dedicated right turn lane exists on a main street approach.
* When a De-Facto right turn lane exists on a side street approach (when right turn volumes on an approach are such that a shared lane actually becomes a dedicated right turn lane by virtue of the distribution of traffic).
* In most cases, right turn volumes on the side street can be discounted if less than 150 VPH. Cases where this is not true are when the right turn volume is the critical lane volume or it is shared in a thru lane and is less than 40% of the total lane volume.

The main question to be answered is: "Is this signal going to primarily serve right turn volumes during a particular time period?" If the answer is yes and there is a need to service right turn volumes because of the long delay they currently are experiencing, then right turns should be accounted for in the analysis.

The third written guideline was provided by Utah Department of Transportation. This guideline was developed using the TEXAS computer simulation model to model an intersection under both non-signalized and signalized control. The assumption made in this guideline is that if right turn volume results in an increase in vehicular delay or an increase in queue formation, it is necessary to include right turn volume when evaluating the need for signalization. A flow chart was developed from the simulation study and it is illustrated in Figure 2. Each of the warrant conditions was checked with 10, 20, 30, 40 and 50 percent of the volume as right turn volumes. Increases in delay and queue length were found to be much more sensitive to the amount of right turn traffic where only one lane is provided on the minor street.

The Highway Division of the Oregon Department of Transportation provided the fourth written guideline. The Oregon guideline is a portion of an official FHWA interpretation of the MUTCD issued in response to an inquiry by the state of Oregon. The FHWA interpretation addresses the situation where the minor street approach consists of one lane for through and left turn movements plus a second lane for right turns only. FHWA's interpretation

RIGHT TURNS TO BE INCLUDED IN SIGNAL WARRANT



V_O = SUMMATION OF ALL CONFLICTING VOLUME IN PASSENGER CAR EQUIVALENTS. $V_O = 1/2\ V_2 + V_1 + V_3$ (IF TWO LANES USE 60 % OF TOTAL VOLUME IN SUMMATION)

V_R = RIGHT TURNS ALLOWED THROUGH GAPS.

N_C = ACTUAL NUMBER OF RIGHT TURNS.

N_A = NUMBER OF RIGHTS TO BE INCLUDED IN WARRANT.

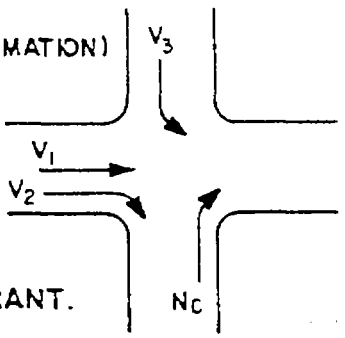


FIGURE 2. UTAH D.O.T. FLOWCHART

states that "right-turn traffic would not be included in the minor street volume if the [right turn] movement operated as a merge, semi-merge or even, with typical intersection geometrics, entered the major street with a minimum of conflict."

In addition to the four questionnaire respondents who reported written quidelines, the authors are aware of one local agency in Arizona that has "written guidelines." Pima County's Traffic Engineering Section evaluates Warrants 1,2,9 and 11 using two different methods:

a) All right-turning vehicles on the minor street are included in the minor street approach volumes;

b) All right-turning vehicles on the minor street are excluded from the minor street approach volume.

The number of hours which satisfy the volume criteria is determined for each method. Engineering judgement is then used to determine whether or not there is a need for a traffic signal. Figure 3 illustrates portions of Pima County's worksheets used for warrant analysis. The figure shows how the right turn volumes are included or excluded on the worksheets.

TRAFFIC SIGNALS MAY BE INSTALLED AND OPERATED ONLY WHEN ONE OR MORE OF THE FOLLOWING WARRANTS ARE SATISFIED.

DESCRIPTION	NUMBER OF LANES FOR MOVING TRAFFIC ON EACH APPROACH: ON MAJOR ST.	ON MINOR ST.	WARRANT REQUIREMENTS: GROUP I: MINIMUM HOURLY VOLUME	# OF 8 HR VOLS ≥ MIN VOL: INCLUDE RT VOL	# OF 8 HR VOLS ≥ MIN VOL: EXCLUDE RT VOL	COMPLIANCE YES: if ≥ 8 NO: if < 8: +RT VOL	COMPLIANCE YES: if ≥ 8 NO: if < 8: -RT VOL	GROUP II: MINIMUM HOURLY VOLUME	# OF 8 HR VOLS ≥ MIN VOL: INCLUDE RT VOL	# OF 8 HR VOLS ≥ MIN VOL: EXCLUDE RT VOL	COMPLIANCE YES: if ≥ 6 NO: if < 6: +RT VOL	COMPLIANCE YES: if ≥ 6 NO: if < 6: -RT VOL
(Choose row that describes intersection)												
WARRANT NO. 1: Minimum Vehicular Volume												
Numbers 1 and 2 must be satisfied.												
1. Major Street Volume (See Table on Page 1)	1	1	500					350				
	≥2	1	600					420				
	≥2	≥2	600					420				
	1	≥2	500					350				
2. Minor Street Volume (See Table on Page 1)	1	1	150					105				
	≥2	1	150					105				
	≥2	≥2	200					140				
	1	≥2	200					140				
WARRANT NO. 2: Interruption of Continuous Traffic												
Numbers 1 and 2 must be satisfied.												
1. Major Street Volume (See Table on Page 1)	1	1	750					525				
	≥2	1	900					630				
	≥2	≥2	900					630				
	1	≥2	750					525				
2. Minor Street Volume (See Table on Page 1)	1	1	75					53				
	≥2	1	75					53				
	≥2	≥2	100					70				
	1	≥2	100					70				

FIGURE 3. PIMA COUNTY WORKSHEETS FOR WARRANT ANALYSIS

WARRANT NO. 9: Four Hour Volumes

The Four Hour Volume Warrant is satisfied when each of any four hours of an average day the plotted points representing the vehicles per hour on the major street (total of both approaches) and the corresponding vehicles per hour on the higher volume minor street approach (one direction only) all fall above the curve in Figure A for the existing combination of approach lanes.

When the 85th percentile speed of the major street traffic exceeds 40 miles per hour or when the intersection lies within a built-up area of an isolated community having a population less than 10,000, the four hour volume requirement is satisfied when the plotted points referred to fall above the curve in Figure B for the existing combination of approach lanes.

# OF POINTS ABOVE CURVE		COMPLIANCE YES: If ≥ 4 NO: If < 4	
+RT VOL	-RT VOL	+RT VOL	-RT VOL

FIGURE A

FOUR HOUR VOLUME WARRANT

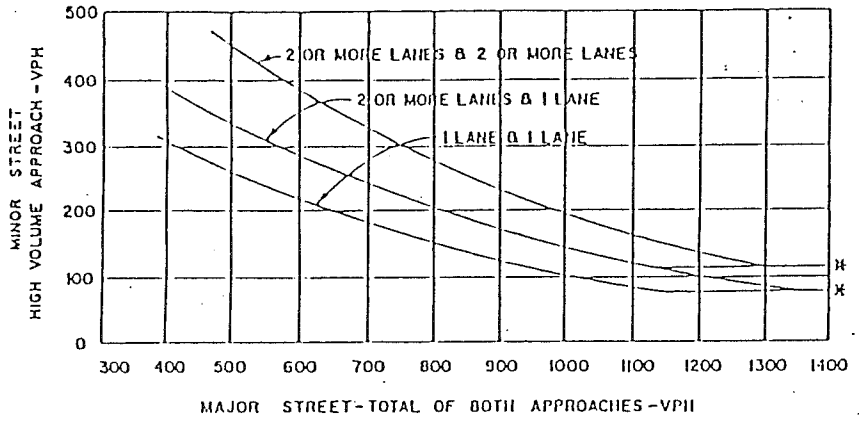


FIGURE 4-3

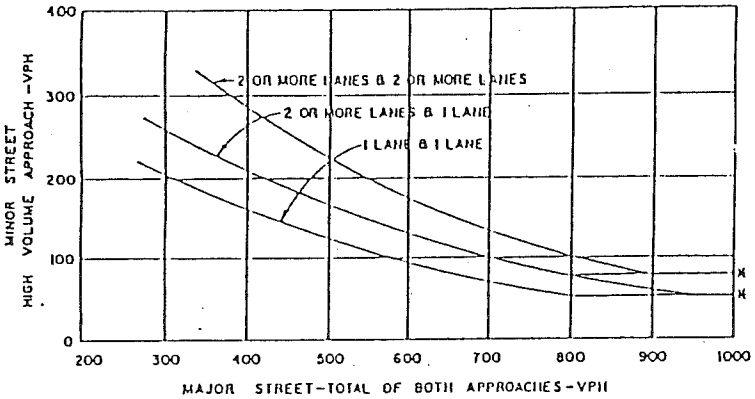
X NOTE: 115 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACH WITH TWO OR MORE LANES AND 80 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACHING WITH ONE LANE.

(REVISED 7/81)

FIGURE B

FOUR HOUR VOLUME WARRANT

(COMMUNITY LESS THAN 10,000 POPULATION OR ABOVE 40 MPH ON MAJOR STREET)



X NOTE: 80 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACH WITH TWO OR MORE LANES AND 60 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACHING WITH ONE LANE.

(REVISED 7/81)

o - SYMBOL FOR PLOTTED POINTS INCLUDING RIGHT TURN VOLUME ON THE MINOR STREET

X - SYMBOL FOR PLOTTED POINTS EXCLUDING RIGHT TURN VOLUME ON THE MINOR STREET

FIGURE 3. (CONTINUED)

WARRANT NO. 11: Peak Hour Volume

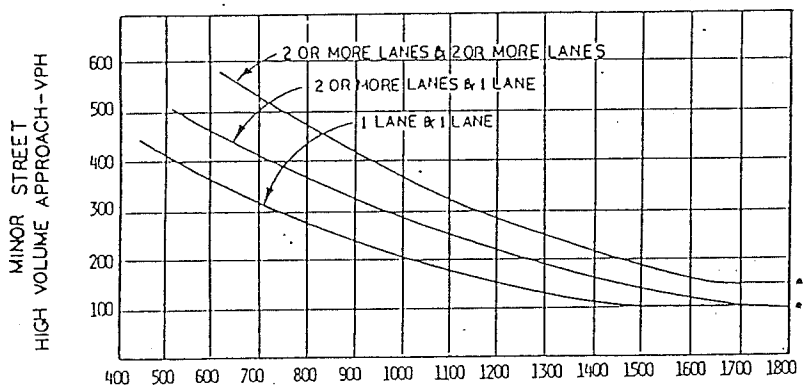
The peak hour volume warrant is satisfied when the plotted point representing the vehicles per hour on the major street (total of both approaches) and the corresponding vehicles per hour of the higher volume minor street approach (one direction only) for one hour (any four consecutive 15-minute periods) of an average day falls above the curve in Figure 1 for the existing combination of approach lanes.

When the 85 percentile speed of major street traffic exceeds 40 miles per hour or when the intersection lies within a built-up area of an isolated community having a population less than 10,000, the peak hour volume requirement is satisfied when the plotted point referred to above falls above the curve in Figure 2 for the existing combination of approach lanes.

COMPLIANCE YES/NO	
+RT VOL	-RT VOL

FIGURE 1

PEAK HOUR VOLUME WARRANT

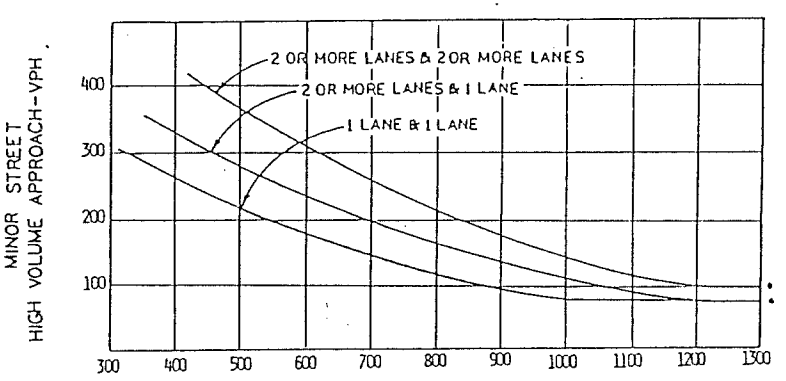


* NOTE: 150 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACH WITH TWO OR MORE LANES AND 100 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACHING WITH ONE LANE.

FIGURE 2

PEAK HOUR VOLUME WARRANT

(COMMUNITY LESS THAN 10,000 POPULATION OR ABOVE 40 MPH ON MAJOR STREET)



* NOTE: 100 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACH WITH TWO OR MORE LANES AND 75 VPH APPLIES AS THE LOWER THRESHOLD VOLUME FOR A MINOR STREET APPROACHING WITH ONE LANE.

⊙ - SYMBOL FOR PLOTTED POINTS INCLUDING RIGHT TURN VOLUME ON THE MINOR STREET

X - SYMBOL FOR PLOTTED POINTS EXCLUDING RIGHT TURN VOLUME ON THE MINOR STREET

FIGURE 3. (CONTINUED)

LITERATURE REVIEW

Perhaps the earliest work published on the subject of traffic signal warrants appeared in Traffic Engineering (1) in 1966. This article described a procedure to develop a warrant for traffic signal control utilizing gap data in the traffic stream. Speed, volume, and headway data were collected at a test site, and charts were developed using this information to relate cumulative distribution of gaps within and between platoons to the length of gap (seconds) for different flow rates. A traffic signal warrant methodology using conditional probabilities was developed. The probabilities of minor street vehicles turning left, driving straight, and turning right and, in doing so, utilizing gaps within and between platoons on the major street are estimated. The total number of gaps expected to be utilized by the minor street vehicles are estimated, which is analogous to the number of vehicles that can be accommodated in one hour on the subject approach when the intersection has no traffic signal control.

During the last two decades, there were four major studies that contained findings related to traffic volume signal warrant problems. The first study, reported in 1967, was initiated to review the warrants published in the 1964 edition of the MUTCD (2). The study thoroughly reviewed the available data and suggested factors applicable to signal warrants. Peak-hour warrants based on delay were outlined. Minimum vehicle volumes on the minor street approaches did not address right turning traffic.

The second study was conducted for the West Virginia Department of Highways and completed in 1975. Its purpose was to develop a warrant that could be used to determine the need for traffic signal at isolated intersections subject to short-duration heavy-volume peaking characteristics (3). Since warrants were established based on limited number of volume-delay counts obtained at selected typical intersections, they were viewed as tentative. The warrants developed contained the following factors:

- o Type of intersection (three-way, "T," or four-way)
- o Number of lanes on the side street approach
- o Minimum total intersection volume
- o Minimum highest side street volume
- o Minimum total delay to side street traffic
- o Percent of left-turns from the main street and left-turn delay

The third study, completed in 1976 by KLD Associates for the National Cooperative Highway Research Program, is probably the most relevant for this state-of-the-art report (4). The main purpose of this project was to develop ten warrants for signal installations. The criterion adopted for the peak-hour warrant indicates a need for a traffic signal to be installed whenever the saturation ratio of traffic demand to capacity on a side street approach exceeds 0.8, for a period of one hour. According to queuing theory, the mean queue at a saturation ratio of 0.8 is approximately four vehicles.

One other criterion applied to the peak-hour volume warrant is that no signal will be installed unless the side street volume equals or exceeds 100 vph (150 vph for a two-lane approach).

Correction tables were developed for four intersection configurations to convert observed side street demand to effective side street volumes based upon the known percentage of right turns. The side street demand is composed of the total volume of traffic on each side street approach (SSV), the associated percentage of right-turn movements (P_R), and the volume of truck and bus traffic (Q_T). For each side street approach, the equivalent volume (Q_{SS}) is calculated by the expression

$$Q_{SS} = SSV + QT$$

which states that one truck/bus is equivalent to two passenger cars.

The following configurations were evaluated:

1. The major street approaches and side street approaches each service one through lane of traffic (configuration 2222, which means two-lane, two-way for one street, and two lane, two-way for the other street)
2. The major street approaches each service two through lanes of traffic; the side street approaches each service one through lane (configuration 4222, which means four-lane two-way for one street, and two-lane two-way for the other street).
3. The major street approaches and side street approaches each service two through lanes of traffic (configuration 4242, which means four-lane two-ways for both streets.)
4. The major street approaches each service three through lanes of traffic; the side street approaches each service one through lane of traffic (configuration 6222, which means six-lane two-way for one street and two-lane two-way for the other street).

Tables 4, 5, 6, and 7 document the correction factors for the four configurations. The Equivalent Side Street Volume (Qss) and the associated percentage of right-turn movements (P_R) are the needed entries for the correction tables to produce the Effective Side-Street Volume (ESSV). The Highest Effective Side Street Volume (HSSV) of the minor street approaches are used to check the peak-hour warrant. Figure 4 displays a sample warrant diagram.

The fourth study was completed in 1982 for the National Cooperative Highway Research Program. It was initiated to evaluate two peak-hour warrants for traffic signal installations (5). The first warrant was suggested by the Signals Subcommittee of the National Advisory Committee (NAC) on Uniform Traffic Control Devices, referred to as the NAC warrant, and the second peak-hour warrant was developed as a part of the third study discussed in the previous section. This second warrant was referred to as NCHRP warrant.

It was concluded from this study that the percentage of right turns on the side street approach is a major factor included in the NCHRP warrant; however, it was not considered in the NAC warrant. A rationale supporting this factor in the warrant is that right turns are made more easily (fewer conflicting movements) than are through or left-turn movements. Right turn delay is a function of the gap distribution of those vehicles approaching from the left on the main street, while through and left-turn maneuvers are affected by the combined gap distribution for both directions of main street flow.

The data collected in this study have verified the importance of the right-turn factor in the determination of peak-hour warrants. There is a wide range in turn percentages at candidate intersections, and the effect of this variation significantly impacts the threshold at which a signal is warranted.

Figure 5 shows the effect of right-turn percentages on the volume threshold of peak-hour warrants for a basic geometric configuration in the proposed NCHRP warrant. Volume threshold means that any point that falls below the curve does not satisfy the peak-hour warrant and any point that falls above the curve satisfies the peak-hour warrant. Also shown on the graph is the NAC volume curve. As indicated, an increase in the percentage of right turns increases the volume threshold at which a signal is warranted.

TABLE 4. IMPACT OF RIGHT-TURN MOVEMENTS: CONFIGURATION 2222*

Equivalent Side Street Volume Q_{ss}	Effective Side-Street Volumes (ESSV) for Indicated Right-Turn Percentages (P_R)							
	10	20	30	40	50	60	70	80
100	90	80	70	-	-	-	-	-
140	130	120	110	100	80	-	-	-
180	170	160	150	140	120	100	80	-
220	210	200	190	170	140	110	100	90
260	250	240	230	210	190	170	150	120
300	280	260	250	240	220	210	190	160
340	310	240	270	260	250	230	220	200
380	350	320	290	280	270	260	250	240
420	390	360	330	310	290	280	270	270

(Rounded to multiples of 10)

*Also 2122, 2211, 2111

Where:

2222 means two-lane, two-way for one street, and two lane, two-way for the other street
2122 means two-lane, one-way for one street, and two-lane, two-way for the other street
2211 means two-lane, two-way for one street, and one-lane, one-way for the other street
2111 means two-lane, one-way for one street, and one-lane, one-way for the other street

Source: Reference 4

TABLE 5. IMPACT OF RIGHT-TURN MOVEMENTS: CONFIGURATION 4222*

Equivalent Side Street Volume Q_{ss}	Effective Side-Street Volumes (ESSV) for Indicated Right-Turn Percentages (P_R)							
	10	20	30	40	50	60	70	80
100	90	80	70	-	-	-	-	-
140	130	120	110	90	80	-	-	-
180	170	150	140	120	100	80	-	-
220	200	180	160	140	120	100	80	-
260	250	230	210	190	160	130	80	-
300	290	270	250	230	200	180	150	100
340	330	320	310	290	250	220	200	170
380	370	360	350	330	300	270	250	220
420	410	400	390	370	340	320	290	270

(Rounded to multiples of 10)

*Also 4122, 4211, 4111

Where:

4222 means four-lane, two-way for one street, and two lane, two-way for the other street
4122 means four-lane, one-way for one street, and two-lane, two-way for the other street
4211 means four-lane, two-way for one street, and one-lane, one-way for the other street
4111 means four lane, one way for one street, and one-lane, one-way for the other street

Source: Reference 4

TABLE 6. IMPACT OF RIGHT-TURN MOVEMENTS: CONFIGURATION 4242*

Equivalent Side Street Volume Q_{ss}	Effective Side-Street Volumes (ESSV) for Indicated Right-Turn Percentages (P_R)							
	10	20	30	40	50	60	70	80
120	110	100	90	-	-	-	-	-
200	190	180	170	160	130	-	-	-
280	260	250	230	220	200	160	-	-
360	340	310	290	270	240	210	130	-
440	370	350	330	310	290	250	200	-
520	420	370	340	330	310	300	240	120
600	500	410	380	360	340	320	300	240
680	570	480	400	380	370	350	330	280

(Rounded to multiples of 10)

*Also 4142, 4221, 4121

Where:

4242 means four-lane two-way for both streets
4142 means four-lane, one-way for one street, and four-lane, two way for the other street
4221 means four-lane, two-way for one street, and two-lane, one-way for the other street
4121 means four-lane, one-way for one street, and two-lane, one way for the other street

Source: Reference 4

TABLE 7. IMPACT OF RIGHT-TURN MOVEMENTS: CONFIGURATION 6222*

Equivalent Side Street Volume Q_{ss}	Effective Side-Street Volumes (ESSV) for Indicated Right-Turn Percentages (P_R)							
	10	20	30	40	50	60	70	80
100	90	80	70	-	-	-	-	-
140	130	120	110	100	90	80	-	-
180	170	160	140	120	100	80	-	-
220	210	200	180	160	130	100	-	-
260	250	240	220	190	160	130	90	-
300	290	280	260	230	200	160	120	80
340	330	320	300	270	240	200	160	120
380	370	360	340	310	270	240	200	140
420	410	400	380	350	310	280	240	190

(Rounded to multiples of 10)

*Also 6122, 6211, 6111

Where:

6222 means six-lane, two-way for one street, and two-lane, two-way for the other street
6122 means six-lane, one-way for one street, and two-lane, two-way for the other street
6211 means six-lane, two-way for one street, and one-lane, one-way for the other street
6111 means six-lane, one-way for one street, and one-lane, one-way for the other street

Source: Reference 4

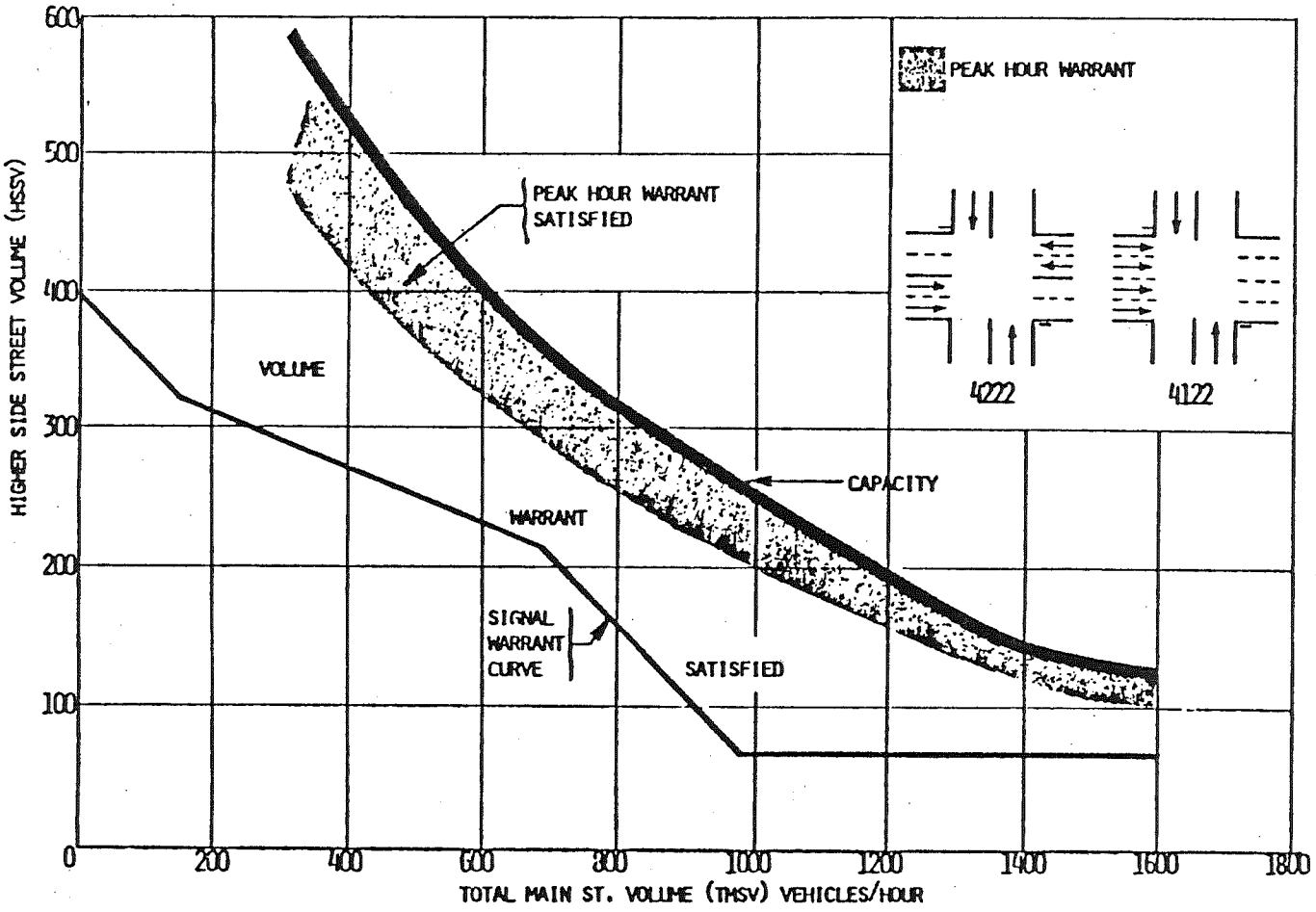


FIGURE 4. VEHICULAR VOLUME AND PEAK-HOUR VOLUME WARRANT DIAGRAM FOR THE 4222, 4122, 4211 AND 4111 INTERSECTION CONFIGURATIONS

Source: Reference 4

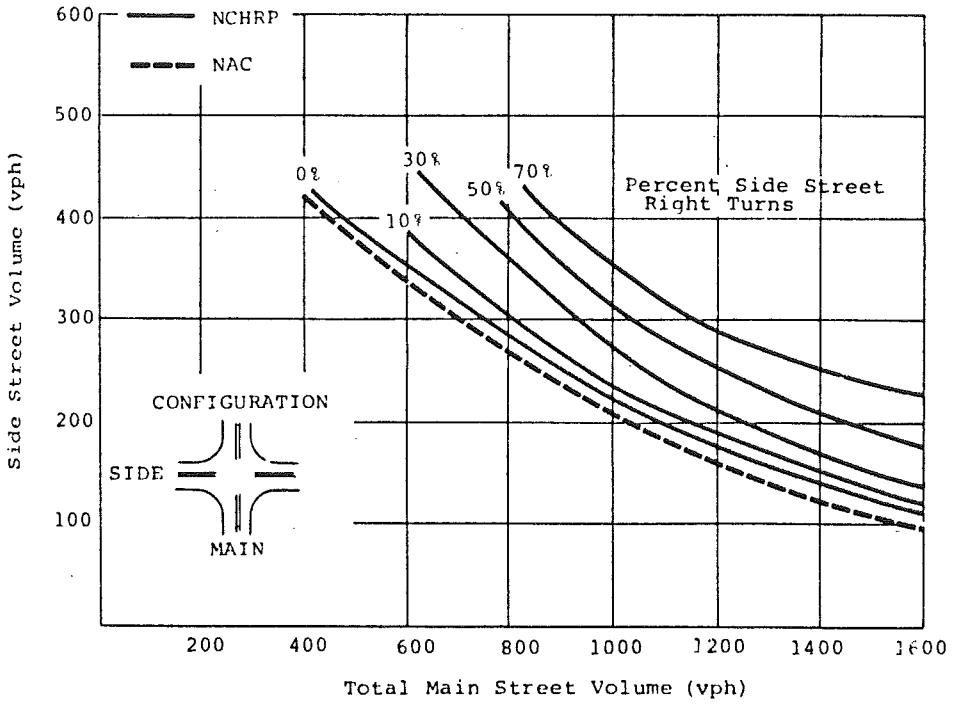


FIGURE 5. COMPARISON OF NAC AND NCHRP PEAK-HOUR WARRANTS -- ONE LANE APPROACHES

Source: Reference 5

Two observations were made; first, the NAC warrant curve is similar to the NCHRP curves; and, second, the NAC warrant is more lenient than the NCHRP warrant for all ranges of percent right-turn traffic.

From the review of both warrants, it appeared that, in general, the NAC warrant criteria would result in more signals being justified than the NCHRP warrant criteria. To test this assumption, both the NAC warrant criteria and the NCHRP criteria were applied to 817, 25-minute observations collected at 241 intersections around the country. The 241 intersection consisted of 115 stop sign controlled intersections and 126 signal controlled intersections. The results are given in Table 8.

TABLE 8. NUMBER OF OBSERVATIONS MEETING NCHRP CRITERIA VERSUS THOSE MEETING NAC CRITERIA.

NAC Criteria	NCHRP Warrant Criteria		
	Not Met	Met	Total
Not Met	370	6	376
Met	134	307	441
Total	504	313	817

Source: Reference 5

The values shown on this table clearly indicate that the NCHRP warrant is the more rigid criteria. Thirty-eight percent of the observations met the NCHRP criteria for installing a signal, and 54 percent met the NAC criteria. This table also shows a relatively high agreement between the two criteria. The two criteria agree that warrants are not met for 370 observations and that warrants are met for 307 observations. In the disagreement cells, there were 134 observations where the NAC criteria were met and the NCHRP criteria were not met.

In conclusion, this analysis showed that the two candidate warrants are distinctly different and that the NCHRP warrant is the more stringent of the two. Furthermore, the percentage of right-turns on the side street approach proved to be an important factor for signal warrant criteria.

Numerous studies have evaluated the effects of Right-Turn-On-Red (RTOR) on delay, fuel consumption, and other traffic measures (6, 7, 8, 9). These studies suggested warrants for prohibition of the RTOR maneuver and reported on delay reductions, fuel reductions, and change of accident numbers at selected sites around the country. Although these studies provided some insight to the effect of RTOR on traffic operations, it has little relevance to the topic of signal warrants. The benefit of these studies would be in the area of warrants for signal removal.

From this literature review, it can be concluded that right-turning percentage is an important factor to be considered in traffic signal warrants. More importantly, the available guidelines for including or not including right turn volumes are very general, do not consider numerous factors, and could be much more refined.

RECOMMENDATION FOR FURTHER RESEARCH

A review of current practice by state, county, and city agencies has shown that while most agencies consider the effect of right turning vehicles when applying the traffic signal volume warrants, very few agencies have any written guidelines. This observation suggests that any consideration of right turning volumes is far more subjective than it is objective. In addition, a review of previous research related to this topic reveals that there has been very little research directed toward the question of: "How much right turn volume should be included (or excluded)?"

If a more objective means of evaluating right turn volumes were available there would be a significant benefit. The risk of making a mistake in deciding whether or not to install a traffic signal would be reduced. A decision to install a signal when, in fact, a signal is not justified does result in signifcant costs for a public agency and the roadway user. The cost of installing a traffic signal is often $25,000 to $50,000 or more. Added road user costs (delay, fuel consumption, vehicle wear and tear, and emissions) could easily be of even larger magnitude each year. If the effect of right turning vehicles could be objectively assessed, and if the presence of large precentages of right turning vehicles occasionally led to the decision not to install a signal, then there could be significant savings to agencies and road users.

For the foregoing reasons it is recommended that research be done to develop objective guidelines for considering the effect of right turning vehicles on traffic signal volume warrants. It is further recommended that the guidelines be developed in a form which are easy for the traffic engineer to apply.

The authors recommend that an intersection simulation model -- the TEXAS Model -- be used to analyze intersection operation and to develop guidelines. Use of simulation will be the most productive and efficient means of evaluating a wide range of intersection conditions. The following section presents a detailed work plan for carrying out this research.

DETAILED WORK PLAN

TASK 1 - IDENTIFY FACTORS TO CONSIDER

The effect of right turn volumes on intersection operation (under minor-street STOP sign control) is highly interrelated to other intersection and

traffic characteristics or factors. For example, the presence or absence of a separate free flow right turn lane can have a significant influence on minor street delay and queue length.

Identify the factors to be considered in the analysis of the effect of right turning vehicles on traffic signal volume warrants. The factors may include some or all of the following; those factors which are selected are not limited to the following list.

Presence or absence of exclusive right turn lane

Presence or absence of a free flow right turn

Sight distance available to right turning vehicles

Percentage of minor street traffic which turns right

Number of lanes on the major and minor street approaches

What turning movements are permitted from each lane

Gap availability on the major street (length, frequency, and distribution of gaps)

Percentage of minor street traffic which turns left

Main street speed

TASK 2 - DETERMINE SIMULATION SCENARIOS

Establish driver, vehicle, and geometry characteristics to be used in running the TEXAS Model. Geometric characteristics shall include, at a minimum, each of the following cases.

Major Street	Minor Street
1 lane	1 lane
2 or more lanes	1 lane
2 or more lanes	2 or more lanes
1 lane	2 or more lanes

Set up individual runs for the driver, vehicle and geometry characteristics noted above. The number and variety of runs shall be sufficient to evaluate the factors identified in Task 1 and to evaluate four different signal warrants - Warrants 1,2,9 and 11. Intersection traffic volumes shall be selected to be approximately equal to those volumes which justify signalization.

TASK 3 - MODEL INTERSECTION OPERATION

Run the TEXAS Model to simulate intersection operation for those conditions set up in Task 2. Each set of conditions shall be run using both Two-way STOP and signalized control.

TASK 4 - EVALUATE SIMULATION RESULTS

Evaluate the simulation results, focusing primarily on minor street delay and queue length. Compare delay and queue length under two-way STOP control versus signalized control. Evaluate the effect on delay and queue length caused by increases in right turn volume or percentage right turns.

TASK 5 - DEVELOP GUIDELINES

Based upon the evaluation done in Task 4, develop guidelines which can be used to determine how much of the right turn volume can be deducted when applying the traffic signal volume warrants (Warrant 1,2,9 and 11). The guidelines may be comprised of tables, figures, nomographs, software, or other formats. The guidelines shall be in a format that is simple and easy to apply.

TASK 6 - PREPARE FINAL REPORT

Prepare a final report which documents the analyses and findings of the research project and which presents the guidelines developed in Task 5.

ANTICIPATED PROJECT DURATION: 5 Months

ESTIMATED BUDGET: $25,000

LIST OF REFERENCES

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9. Guidelines for Treatment of Right-Turn Movements on Rural Roads (Abridgement); Cottrell; Transportation Research Board N855, pp. 47-49.